

Flat Panel Display Metrology -- Less than Meets the Eye

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ABSTRACT

Accurate measurement of electronic displays has become important in recent years owing to the advances in flat panel display technologies. A well-defined language is needed to specify, evaluate, and compare display technologies and their suitability to tasks. Such a specification language depends upon an unambiguous metrology being firmly in place to provide a level playing field. We will review some of the unanticipated complications that have arisen in simple measurements such as contrast as well as more complicated measurements such as display reflection properties.

INTRODUCTION

The goals of metrology and any associated standardization processes include the attainment of uniformity around the world. In the case of electronic displays and especially flat paned displays (FPDs), a standard language needs to be in place in order to intelligently communicate display quality and, for example, specify display characteristics for procurement purposes. However, that standard language needs to rest upon a foundation of good metrology to avoid confusion. With the highly competitive display industry growing at an alarming rate, good metrology becomes a factor in the competition process. Not only do people want to carefully specify their displays, but also manufacturers want to meet the needs of the users, and then the users want to assure themselves that they are getting what they paid for. Complicating the problem is that display requirements are task dependent. A display that looks great on the office desk may be unsuitable for use in a dark room, and vice versa. A display technology that is wonderful for a laptop may be unsuitable for a helicopter console or a monitor used for radiology.

What is interesting is that the eye can tell within a short time (less than a second) just how good the display "looks" for its intended use, whereas it may take a measurement lab hours to quantify

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the display's performance. The eye is a spectacularly designed device that sees things that the instrumentation sometimes cannot. Thus, one of the problems in display metrology is assuring that the metrology employed can measure what the eye sees. Unfortunately, for some measurement methods and equipment, the instrumentation "sees" with substantially less quality than does the eye—unknown to the operator of that equipment. The conclusions drawn from such faulty measurements can be inadequate or incorrect. Further, conformance standards based on inadequate metrology can lead to a sloppy lab making a bad measurement on a good display and disqualifying that display for use in a particular market. Conversely, a good lab making a good measurement on a bad display can qualify that bad display for use because the performance criterion was set too low by an inadequate conformance standard based upon sloppy metrology.

We will examine two areas of display metrology where the eye can often see much better or much differently than the measurement equipment that is normally employed: (1) accurate luminance (and color) measurements (especially of non-trivial patterns) and (2) measurements of reflection. Whereas the science of light measurement suffers from not having highly accurate transfer standards or basic standards (the current accuracy is on the order of 1% expanded uncertainty with a coverage factor of two), the problems we are addressing here go far beyond the intrinsic errors of photometry and colorimetry. The problems we are discussing arise from expecting more from the instrumentation than it can deliver and the oversimplification of a complicated measurement problem. These problems are aggravated because of the reluctance of the industry to think in terms of diagnostics and laboratory maintenance—a neglected but necessary expenditure in order to compensate for the lack of accurate basic standards for light measurements.

VEILING GLARE AND LUMINANCE MEASUREMENTS

Veiling glare arises in all optical systems. Because of scattering and reflections within the optical system, light from one part of a scene is scattered into the wrong part of the image. Lens flare in photography (those multicolored blobs of light arising from a bright light in the field of view) is a worst-case example of this kind of scattering. However, unlike lens flare, veiling glare is not always obvious or even visible in the instrumentation. Figure 1 shows an example of the origins of veiling glare in a photopically corrected, thermoelectrically-cooled (TEC), charge-coupled-device (CCD) camera. Because of reflections between the lenses and other parts within the camera, light from one region in the object (in this case the white area) can corrupt a different region in the image (in this case the black rectangle). Two fictitious rays are traced showing this veiling-glare corruption process. The photographs at the bottom of Fig. 1 show the exaggerated effects of veiling glare and lens flare.

Veiling glare is something that we have to anticipate and be able to counteract if we want to make accurate light measurements. If the image or pattern is complicated, being composed of a range of luminance values and colors, we can anticipate mixing of colors and corruption of luminance values from glare unless we take measures to either eliminate the problem or account for it in the analysis of the image. Even in the simple case of measuring a full screen color (white, black, red, green, blue, whatever), although there is no danger of mixing colors, there is a danger of corrupting the luminance reading. In Fig. 2 we show a luminance meter measuring a white full-screen with and without the aid of a flat mask of opaque matte black material. The full screen subtends 15° from the front of the lens whereas the hole in the mask subtends 1.5° . Three

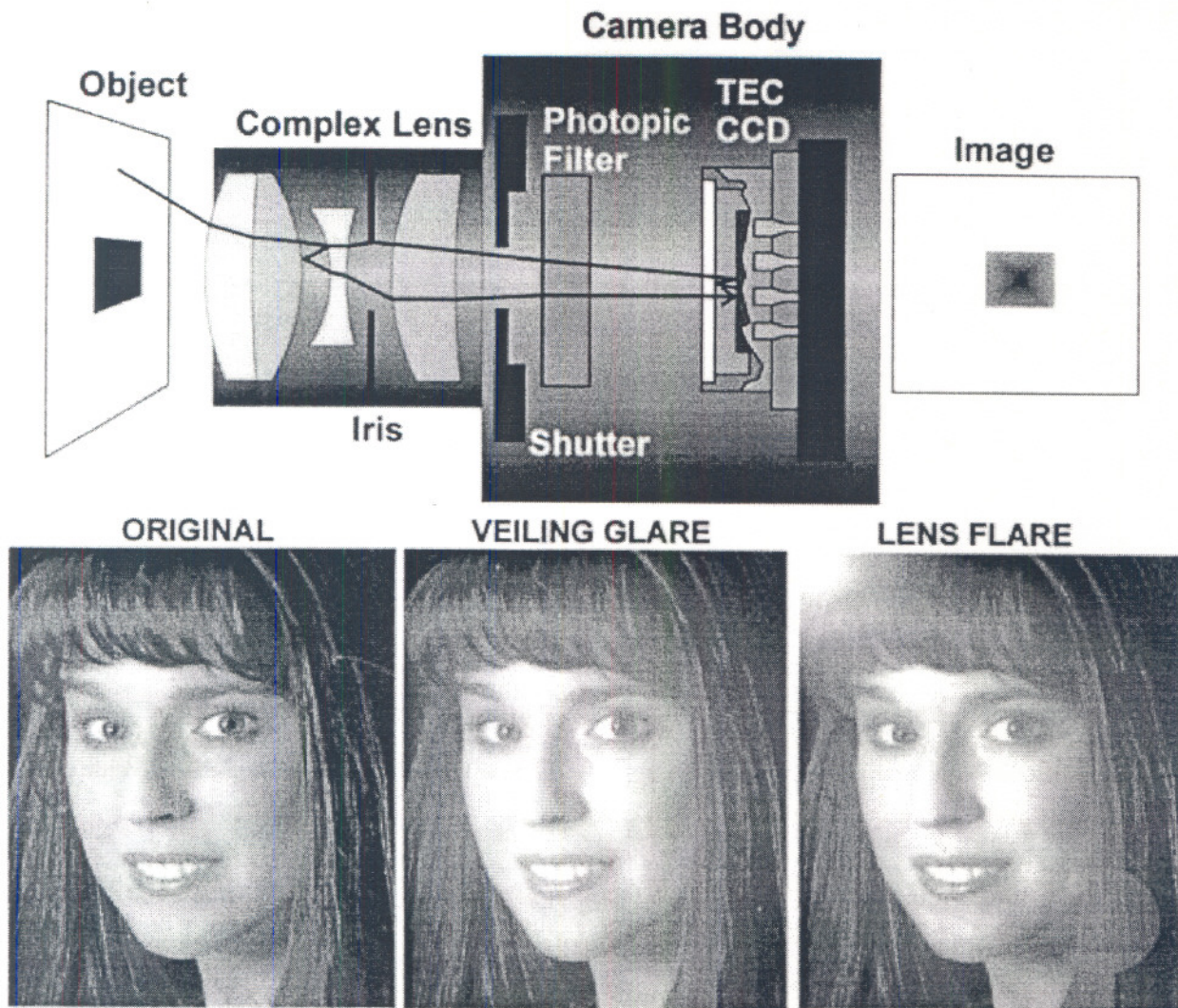


Figure 1. Origins of veiling glare and lens flare.

difference luminance meters are used. The increase in the luminance reading when the mask is removed is 0.4 % for instrument #1, 1.3 % for instrument #2, or 4.8 % for instrument #3. If we were not aware of the fact that veiling glare is a problem and we happen to be using instrument #3 to qualify a new line of candidate flat panel displays (FPDs) for use, we might pass an inferior display. That is, if the acceptance criterion is 100 cd/m² or larger for screen white after a 20 min warm-up, and we measure 100 cd/m² without using the mask, we would pass a display that really doesn't qualify since it's luminance, if measured properly, is 95.4 cd/m²; and the display should be rejected. Our luminance meter may be well calibrated when using a source having a small solid angle, but that calibration may not be suitable for sources that have a large subtense. Many users of luminance meters are unaware of such problems.

Aside: Since the eye is not very sensitive to small changes in white luminance, some might argue that this small error in white measurement couldn't be a big problem. That is true. But the lighting world chose a linear unit of light measurement based upon a vision model whereas the eye is more logarithmic than linear—as is the ear. It is truly unfortunate that the lighting world

didn't take some clues from the sound world. In the sound world they measure the sound spectrum uniformly from 20 Hz to 20 000 Hz. Various loudness contours are known, but they are not applied to the basic measurement unless there is a particular reason to do so. Everybody knows a 1000 Hz tone is much louder to the ear than a 100 Hz tone of the same sound pressure level. But they generally don't complicate the measurement by incorporating a loudness contour (a contour that may not apply in all cases) to the basic spectral measurement. Further, the sound world uses a log unit of measure, the decibel (dB) that approximates the way the ear hears. This way, they won't be accidentally misled into thinking something is important when it is not.

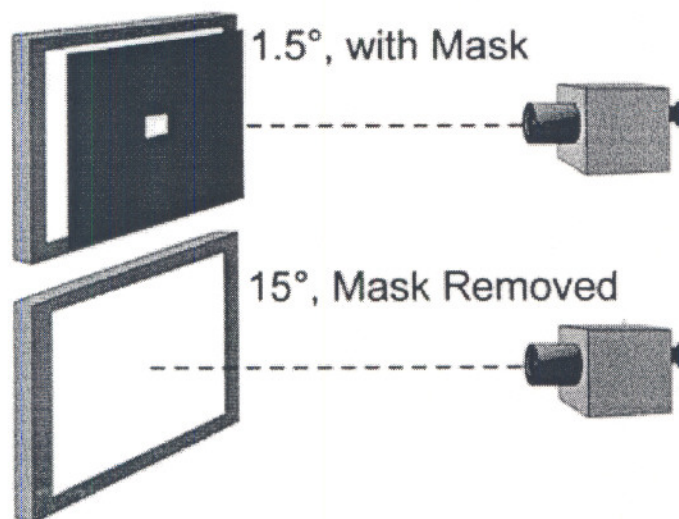


Figure 2. Measurement of white full screen with and without the aid of a mask to reduce veiling glare.

Had the lighting world copied the sound world, we would all be measuring the radiance spectrum from 400 nm to 700 nm using a log-based unit of measure, perhaps the “decibulb” (and then we would have the same symbol, dB). We would all know that the eye can't see as well in the red or blue than in the green, but most of the time we wouldn't need to incorporate that information into the metric. (We would also know that we could see beyond the 400 nm-700 nm range just as some of us can hear beyond the standard audio range.) With such a metric, the difference between 100 cd/m^2 and 101 cd/m^2 would be 0.043 dB, but if we added that same amount of light, 1 cd/m^2 , to a black level of 0.5 cd/m^2 we would have a difference of 4.8 dB. This is much more in line with how the eye sees the introduction of the small amount of light—it is inconsequential to white but significant to black. Once we have the spectral data, then we can apply whatever vision model we want to analyze the results. But the advantage of the decibulb would be that we have a basic metric that provides a reasonable indication of what we see. We would not be misled into worrying about small changes in white as being significant.

Photometry incorporates a vision model to obtain a measure of luminance (cd/m^2) that is not the same as brightness. Luminance characterizes the spacio-temporal response of the eye. To see how poorly luminance can be associated with brightness, we can place three fully saturated large patches of red, green, and blue on a computer monitor and adjust them so that their luminances are the same. We will see that the green is very much less bright than the red and blue. (How

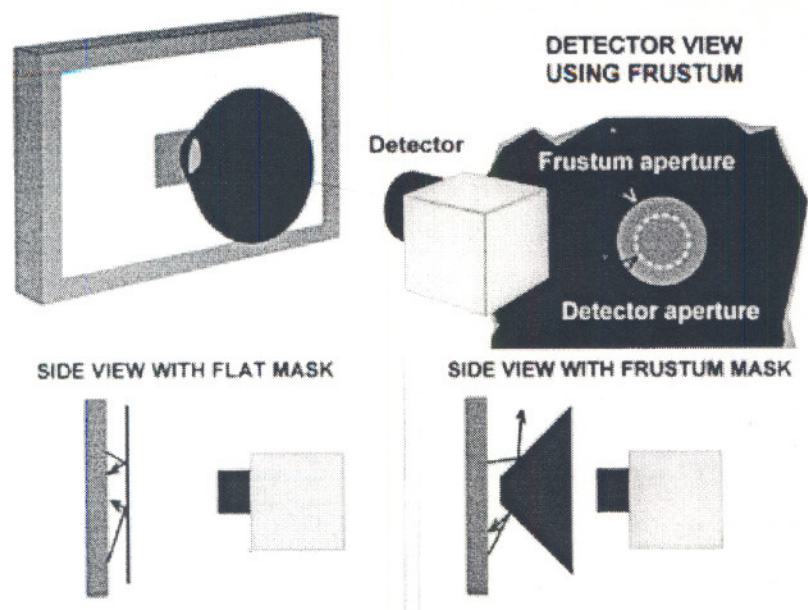


Figure 3. Use of frustum mask to control veiling glare.

bright we judge the patches will depend upon the surrounding conditions.) But if we placed some small black letters in those equal-luminance patches, we would find that we could read them approximately equally as well in each patch as we step back from the computer monitor. Providing the vision model as a part of the fundamental metric can produce results that might be misleading unless we are well informed. Clearly, measuring the spectral radiance can involve more expensive equipment, but it gives us more to work with and allows us to massage the data according to any vision model we wish. End of aside.

Like it or not, the lighting world presently uses a linear photopic metric; and a small error in the measurement of white can, therefore, have economic impact. Standards sometimes draw hard lines associated with some criterion. Pass-fail can depend upon how well the measurement is made. If significant errors can be made in white measurements, what about black measurements? Whereas a measurement of a full-screen black with and without a mask can manifest the same veiling glare error as does the measurement of white, if we remain ignorant of veiling glare, the measurements of checkerboard contrast or halation can have enormous errors—the contamination from white light can appreciably add to the darkness of the black, even completely overshadowing the true black luminance.

Consider a halation measurement where a black rectangle appears at the center of a white screen. The size of the black rectangle is varied from a small fraction of the screen's linear dimension, say 5 %, to full screen black in steps of 5 % or 10 % of the screen's linear size. This measurement looks for how the display's white regions corrupt the black central region. When this kind of corruption occurs, small areas of black get washed out and the display loses its contrast or dynamic range. How bad can it get? Suppose we have a FPD that has a white luminance of 100 cd/m^2 and is able to support a contrast of 250:1 so that the black luminance is 0.4 cd/m^2 . Suppose we have a standard that requires that the display, under worst-case halation conditions of a 5 % diagonal box, have a contrast of at least 100:1. If we fail to account for veiling glare by not using a mask during the halation measurement, we can—for example, by

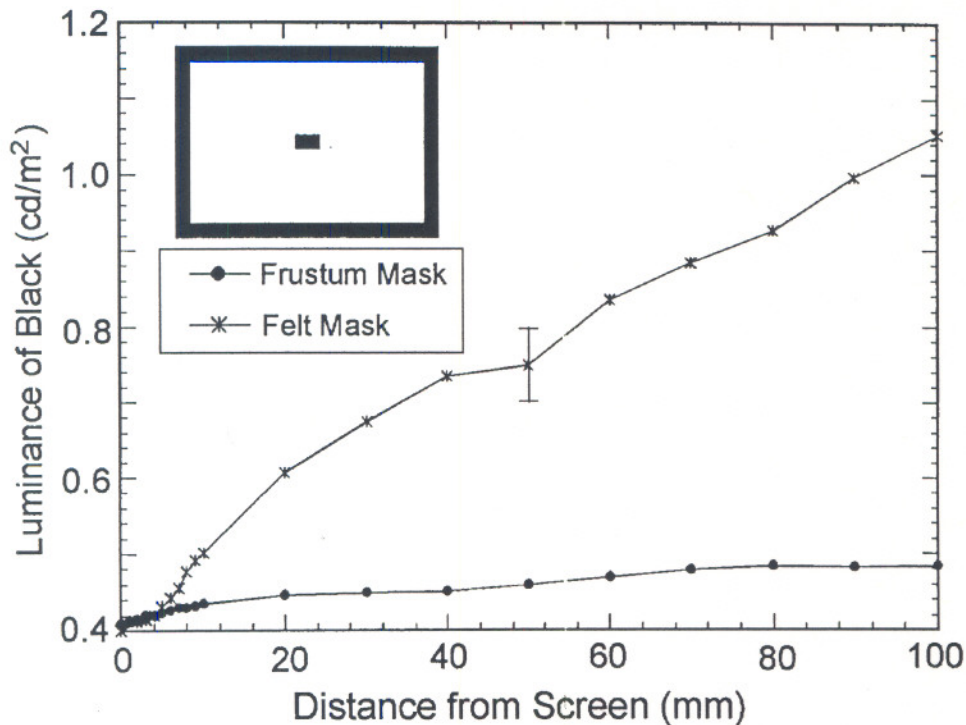


Figure 4. Comparison of frustum mask with black felt mask in halation measurement.

using instrument #3—introduce 4.8 % of the white into the smallest black region measured. We would then conclude that the black would have a luminance of 5.2 cd/m^2 and the display would seem to support only a contrast of 19.3:1 or less for small area blacks. That is less than the contrast of common copy paper using xerography (about 20:1 to 25:1). However, to the eye it looks much better than copy paper. The instrument, if trusted, “sees” less than the eye can see in appreciating the blackness of the display. Since most people trust the instrumentation over and above what the eye sees, the display would be rejected as unsuitable.

If we want to be especially careful in a halation measurement, we may even find that a flat mask is not the best kind of mask to use in several situations—see Fig. 3. A frustum of a cone (a cone with the apex end cut off) having an apex angle of 45° can be found to be useful. Such frustums can be made of thin gloss-black plastic material. If sufficiently black material cannot be obtained, a thin plastic sheet can be painted with the best gloss-black paint available. Whenever a flat mask (perhaps made of black felt) cannot be placed against the screen then a frustum should be used. This can happen either because of heating effects, because of the front surface being placed a distance from the pixel surface, or because the screen is a prototype and cannot be touched. If the flat mask is moved away from the pixel surface, light from the white areas can be reflected back onto the screen and contribute to the black measurement. Because of the gloss surface of the frustum the light from the surrounding white areas are kept away from the black region. The only stray light that can contribute to black is from the Lambertian reflection properties of the gloss surface, which, by virtue of the shape of the frustum is mostly kept far away from the screen.^(1,2) In Fig. 4, we show a flat-frustum mask comparison of a halation measurement made on a laptop computer display that has a contrast of approximately 250:1. We employ a very good flat mask material (made of black felt) and a frustum mask made of gloss-

black plastic. Only when the flat mask is against the FPD surface will it compare well (or exceed) the performance of the frustum mask. When the mask is against the FPD surface the temperature of the surface will increase and the performance of the FPD can be affected.

In many cases, such as the checkerboard and the halation measurement, the eye will perceive a much higher contrast than most instruments would indicate unless the veiling glare in the instrument is eliminated. This is not to say that the eye does not have veiling glare, it does. But at least for young people who don't suffer from disability glare problems, the eye has less veiling glare than most instruments. The eye has only one surface of high index-of-refraction change (the front surface) that typically produce reflections in complex lenses. The eye is liquid or solid from its front surface to the retina. An investigation is underway to simulate the design of the eye in developing a camera that has very little veiling glare.⁽³⁾

REFLECTION MEASUREMENTS

Measuring the performance of a display in a darkroom laboratory is only part of the problem. Most displays are used in high-ambient light environments so that their reflection performance needs to be characterized as well. The problem is that many FPDs today have reflection properties that differ greatly from television displays and older cathode-ray-tube (CRT) computer monitors. These newer reflection properties can be much harder to characterize. When people speak of reflection, they often think of specular and diffuse reflection. Specular is mirror-like and diffuse is matte. When we think of mirrors and their images of objects we realize that the luminance L (or brightness) of a virtual image seen in the mirror is proportional to the source luminance L_s (or brightness) of the object

$$L = \rho_s L_s, \quad (1)$$

where ρ_s is called the specular reflectance. Most regard "diffuse" to mean Lambertian, which is somewhat misleading. A Lambertian reflector appears to have the same luminance no matter from which direction its surface is viewed, and the luminance L is proportional to the light hitting the surface, the illuminance E ,

$$L = qE, \quad (2)$$

where q is the luminous coefficient. Reflection from most objects and especially modern FPD as well as CRT screens cannot usually be characterized by such simplistic reflection properties as in Eqs. (1) and (2). Unfortunately, most of the measurements methods that have been devised to measure reflection of displays have, at least implicitly, assumed that the above two components provide an adequate description. However, there exists three components of reflection—not just two—and the third component, haze, is very difficult to measure.

The best way to observe the three reflection components with the eye is by using a point source of light. Flashlights are readily available where the reflector can be screwed off exposing a very small bulb that serves well as a point source. When we examine the reflection of the point source in many of the high-quality CRT computer monitors available today, we can usually see three components of reflection.⁽⁴⁾ The Lambertian component is the general dark-gray of the phosphor

screen behind the face plate. The specular component with a distinct image is visible off the front glass surface of the face plate. The haze component is the fuzzy ball around the specular component. Often a more pronounced haze component is found on the phosphor screen behind the face plate that follows the specular image but is not perfectly aligned with it as the point source is moved around. You will note that as the point source is moved away from the screen the Lambertian component is reduced and the haze components (from both surface) also are reduced. That is because both Lambertian and haze are similar in that they are proportional to the illuminance. The haze is also similar to the specular component producing a distinct image in that the haze is peaked in the specular direction. That is why it follows the specular image as the point source is moved—see Fig. 5.

One problem is that the haze component is affected by the geometrical configuration of the apparatus and is difficult to measure reproducibly.⁽⁵⁾ That is, the size of the light source, its cross-sectional uniformity, its distance from the display, the size of the entrance pupil of the detector, the detector distance from the screen, etc., all can affect what reflection luminance is measured whenever haze is nontrivially present as a reflection component. To determine what the eye will see as reflection requires a detector that has the same subtense as does the eye under normal viewing conditions—the angle defining the solid angle of the entrance pupil of the detector must be the same as that of the eye.

The other problem is that most FPDs will ultimately be seen with reflection properties that only have a haze component. Many displays that are now seen on laptops essentially don't have either a Lambertian component or a specular component of any significance. What can be measured as a Lambertian component, if anything at all, is often four or five orders of magnitude below the peak of the haze component (the brightest part of the fuzzy ball). That is often not the case with CRT displays where the specular component can dominate the reflection especially for discrete sources such as windows and lamps.

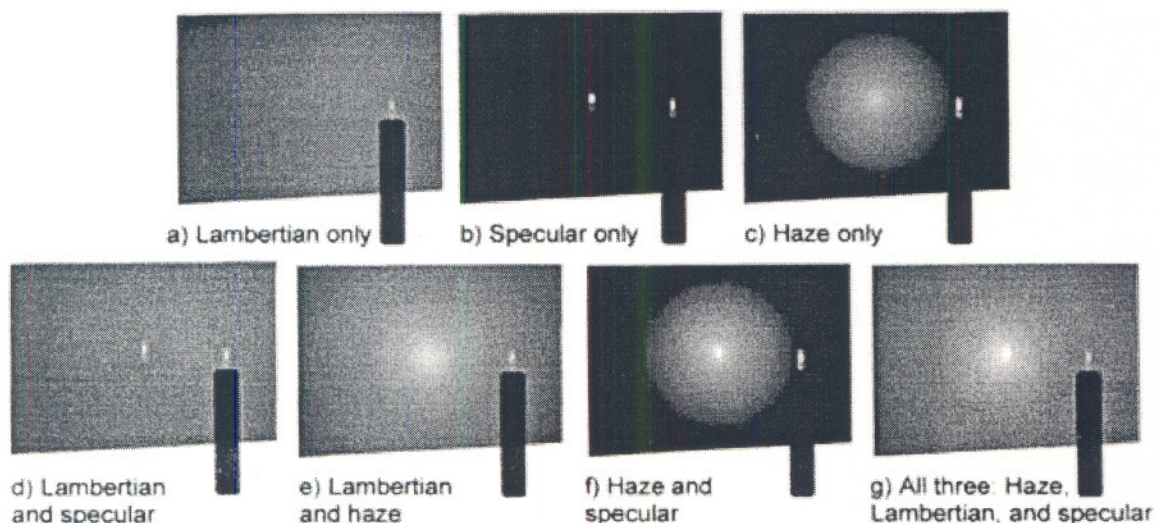


Figure. 5. Illustration of the three components of reflection using a point source of light.

The reflection properties are best measured by the bidirectional reflectance distribution function (BRDF).^(6, 7) It is the generalized relationship between the illuminance and the luminance. One formulation of it is similar to Eq. 2 but in differential form:

$$dL(\theta_r, \phi_r) = B(\theta_r, \phi_r, \theta_i, \phi_i) dE(\theta_i, \phi_i) \quad (3)$$

This relates the illuminance from an element of solid angle dE in the incident direction (θ_i, ϕ_i) to the element of luminance dL contributing to the observed luminance in the reflection direction (θ_r, ϕ_r) . In this formalism the specular component becomes a delta function, the Lambertian component is flat (independent of direction), and the haze is an intermediate state between the two extremes of specular and Lambertian—usually a very peaked bell-shaped curve.⁽⁶⁾ The BRDF $B(\theta_r, \phi_r, \theta_i, \phi_i)$ in the above formulation neglects a possible wavelength and polarization dependence that could be included. The measurement of the BRDF is very difficult, time-consuming, and can involve very expensive apparatus. Alternative measurement methods adequate for displays are currently under consideration.^(6, 7) The BRDF for a surface such as in Fig. 5g is shown in Fig. 6.

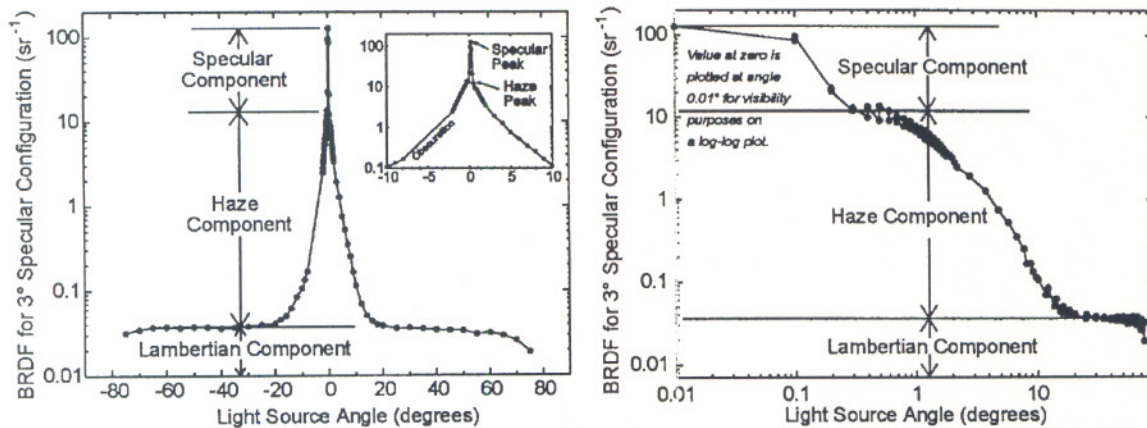


Figure 6. Sample BRDF of material exhibiting all three components of reflection.

In the case of measurements for reflections, what the eye sees can be very different from what the instrumentation measures unless we go to a great effort to carefully control the measurement apparatus. Whenever oversimplifying assumptions are made about the reflection properties, the measurement errors can be a factor of two or larger from laboratory to laboratory. The importance of accurate and reproducible reflection measurement methods is clear whenever there is a performance criterion to be met. However, not only must the measurements be reproducible, but in order to be meaningful to human observers, the methods used also need to reproduce what the eye sees. In the case of a reflection measurement using a wide diameter lens on a detector placed near the display surface it is possible that reproducible measurements can be made provided all the geometrical parameters are controlled. However, for such an apparatus, the measured reflectances can be much less than what the eye perceives whenever haze complicates the reflectance properties.

CONCLUSION

The display industry is experiencing an explosive growth. Competition between technologies and between manufacturers demand a well-defined specification language based upon reproducible metrology. Much of what makes a display useful depends upon how that display produces light and deals with reflections from the surround. Critical measurements of non-trivial test patterns are complicated by veiling glare in the optical system of the instrumentation used to measure the light. Masking must be employed if the light measurements will properly duplicate what the eye can see. Whenever reflection characterization is called for, the measurement instrumentation must be evaluated to be sure that it is capable of adequately dealing with the haze component of reflection. This usually calls for careful arrangement of the geometrical parameters of the apparatus and attention given to the subtense of the detector's lens from the point of view of the detector as being similar to that of the eye. These two issues demonstrate that a casual attitude regarding display metrology can be rewarded with terribly poor measurement results. Unless due care is taken and diagnostics considered, the instrumentation measurements will be less than what meets the eye.

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